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Wide Frequency Tuning in Resonant-Tunneling-Diode Terahertz Oscillator Using Forward-Biased Varactor Diode

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Abstract

We fabricated a terahertz (THz) voltage-controlled oscillator (VCO) using a resonant tunneling diode (RTD) integrated with a varactor diode and measured the frequency dependence of the RTD VCO with a DC sweep from -4 to +0.8 V. A wide and abrupt frequency tuning of 130 GHz (600–730 GHz) was obtained when a forward-biased voltage (from +0.4 to +0.8 V) was applied to the varactor diode. The wide frequency tuning was achieved using an admittance change in series-connected air-bridge inductance and the forward-biased varactor diode.

1. Introduction

In the terahertz (THz) frequency range, spectroscopy is an important application using the specific absorption spectra of a variety of molecules [1], [2]. If semiconductor THz sources with a wide frequency tuning range exist, very compact spectroscopic chips without external sources can be developed, and this would simplify the design of systems for THz spectroscopy. Quantum cascade lasers with a tuning range of ~10% have been reported [3]. However, low-temperature operation and a complicated mechanical tuning system were required for these lasers. Voltage-controlled oscillators (VCOs) that use high-speed transistors in the terahertz range have also been studied [4]. Although the VCO can operate under room-temperature conditions, the tuning range is less than 5%. Resonant tunneling diodes (RTDs) are good candidates for compact THz sources oscillating at room temperature [5]. We proposed and fabricated RTD VCOs and achieved frequency tuning by varying the capacitance of the integrated varactor diode under reverse-bias conditions [6]-[8]. In this study, we measured the frequency dependence of the RTD VCO on the forward-bias voltage of the varactor diode and achieved wide frequency tuning of 130 GHz. The tuning mechanism is briefly described.

2. Experimental Results and Discussion

Figure 1(a) shows a schematic illustration of the structure of the RTD VCO. Microphotographs of the RTD VCO are shown in Fig. 1(b). An AlAs/InGaAs double-barrier RTD and varactor diode mesas were integrated into the slot worked as a cavity and an antenna. The RTD has a negative differential conductance (NDC) that is used for terahertz oscillation. The varactor diode consists of three layers: p^+-InGaAs (1×10^{20} cm^{-3}, 100 nm)/n-InGaAs (6×10^{16} cm^{-3}, 400 nm)/n^+-InGaAs (5×10^{19} cm^{-3}, 100 nm). An InGaAs abrupt-junction varactor diode was employed, and these layers were grown on the RTD layer. The depletion layer only extends into the n-InGaAs layer when a reverse-bias voltage is applied because the doping concentration in the p^+-InGaAs is much higher than that in n-InGaAs layer. The capacitance and series resistance of the varactor diode decrease as the reverse-bias voltage increases. Two metal–insulator–metal (MIM) capacitors were formed on each side of the slot antenna and were connected to the RTD and varactor diode mesas. These MIM capacitors shunt the terahertz wave to form a standing wave in the slot while it is opened at the direct current for biasing. The RTD and varactor diode can be operated with different bias voltages using the separated electrodes. The bottom electrodes for the RTD and varactor diode are common. In this study, we fabricated a RTD VCO with a 19-µm-long slot antenna, a 1.1-µm^2 RTD mesa, and a 8-µm^2 varactor diode mesa.

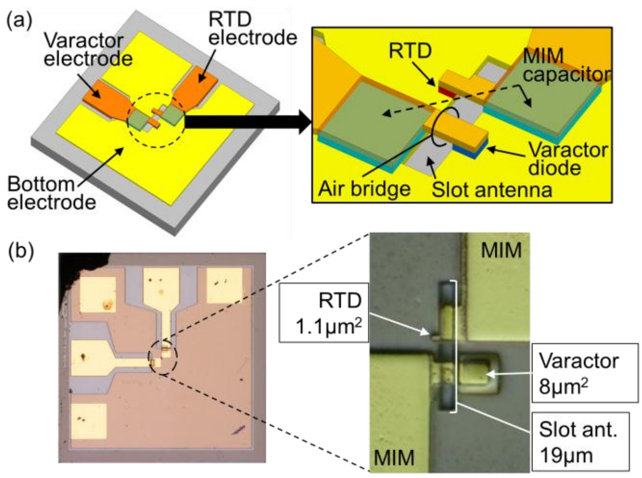

Fig. 1 (a) Schematic structure of the RTD VCO, and (b) microphotographs of the fabricated device.

We measured the tuning range of this RTD VCO with a DC sweep from –4 to +0.8 V. Figure 2 shows the dependence of the oscillation frequency of the RTD VCO on the bias voltage to the varactor diode. In the reverse-bias voltage (DC sweep from –4 to +0.4 V), the oscillation frequency decreased from 680 to 600 GHz. On the other hand, the oscillation frequency increased steeply from 600 to 730 GHz with the forward-bias voltage (from +0.4 to +0.8 V). V-shaped tuning characteristics were obtained, and wide frequency tuning with the forward-biased varactor diode was achieved compared to the reversed-bias operation.

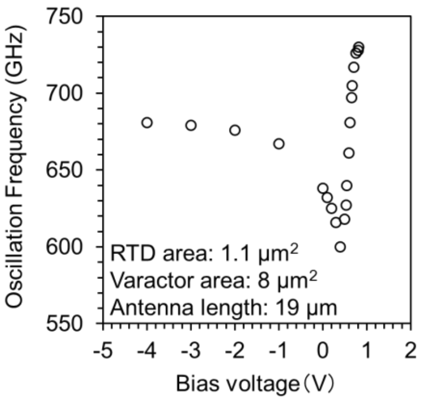

Fig. 2 Dependence of the oscillation frequency on the bias voltage from -4 to 0.8 V.

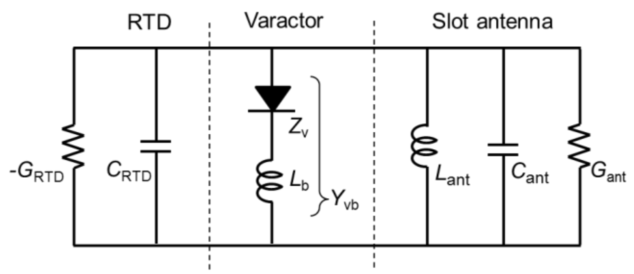

Fig. 3 Equivalent circuit of the RTD VCO in the THz range. Air bridge inductance is connected in series with the varactor diode.

The tuning characteristics can be explained qualitatively by the variation in the impedance of the varactor diode due to the bias direction. Figure 3 shows the equivalent circuit of the RTD VCO in the THz range. G_{ant}, L_{ant}, and C_{ant} are the radiation conductance, inductance, and capacitance of the slot antenna, respectively. G_{RTD} and C_{RTD} are the NDC and capacitance of the RTD, respectively. L_b is the inductance of the air bridge between the varactor mesa and the MIM capacitor. Z_v is the impedance of the varactor diode mesa, which is connected in series with L_b. An oscillation is obtained when G_{RTD} compensates for the resonator losses. The oscillation frequency is determined by the condition that the imaginary part of the total admittance of the whole circuit is equal to zero. In the reversed-bias condition, the depletion layer of the varactor diode is extended, and Z_v is thus capacitive and is expressed as $1/j\omega C_v$, whereas C_v is a variable capacitance due to the depletion layer of the varactor diode. The impedance of $1/j\omega C_v$ is high compared to $j\omega L_b$, and the total admittance Y_{vb} is almost equal to $j\omega C_v$. Frequency tuning can be obtained by variable capacitance C_v with reversed-bias voltage. We have reported on an RTD VCO that uses this conventional mechanism [6]-[8]. In the forward-bias condition, the varactor diode depletion layer becomes thin and vanishes, and diode current flows. Therefore, Z_v can be expressed simply as R_v, whereas R_v is a variable diode resistance. In this condition, Y_{vb} can be expressed as $1/(R_v + j\omega L_b)$. The imaginary part of Y_{vb} of $-j\omega L_b/(R_v^2 + \omega^2 L_b^2)$ can be controlled by the variable resistance R_v, and frequency tuning in the forward-bias direction was achieved by this mechanism.

3. Conclusions

We fabricated an RTD VCO integrated with a varactor diode and measured the frequency dependence of the RTD VCO with a DC sweep from -4 to +0.8 V. A wide and abrupt frequency tuning of 130 GHz (600–730 GHz) was obtained when a forward-bias voltage (from +0.4 to +0.8 V) was applied to the varactor diode. The tuning mechanism in the forward-bias direction was briefly explained using an equivalent circuit model.

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